

Patent Application of
Ted Humphrey
for
TITLE: Analog Electronic Device

CROSS-REFERENCE TO RELATED APPLICATIONS

This patent claims in one of its dependant claims the use of the proposed device to create an amplifier where the amplifier can under certain conditions be viewed as a current amplifier which is the subject of a related co-pending patent application.

In more detail, the other co-pending application is titled "Symmetrical Current Amplifier" submitted by Ted Humphrey in July 2003. Under certain conditions, Claims 6, 7, 8 and 9 of this patent titled "Analog Electronic Device" and Figures 13, 14, 15 and 16 (and some later numbered Figures which include an amplifier), have the appearance of a current amplifier. This condition appears when the amplifiers are being driven by signals classified as currents rather than voltages. Such a classification is determined by the impedance of the signal. Under these conditions, the output current is either dependent on the input current or the difference of input currents. The amplifier designs taught in this patent depend on claims 1, 2 and/or 3 and the unique relationship or synergy that has been discovered about this connection of two transistors. These teachings are not included in the related co-pending application and are not obvious from that application. Therefore the amplifiers taught in this patent could not be included in that patent. These teachings show new unique ways to design an amplifier using the basic device, the core of this patent, that are an improvement over what could be designed before this invention. But the design of amplifiers is not the thrust of this patent. The thrust of this patent is that there is a building block that can be used in many different ways to design an array of circuits. There is no common structure between the two patnets.

DESCRIPTION

FIELD OF INVENTION

This invention relates to the design of electronic circuits and proposes a new building block that makes it easier to design complex analog circuits and improve their performance while simplifying them.

PRIOR ART

There are four areas of prior art to examine. Also a quick statement concerning the dependant claims.

The four areas are:

- 1) The Darlington Patent 2,663,806
- 2) Current sources

- 3) Current mirrors
- 4) Current limit circuits.

The Darlington Patent

The first is the patent for the “Darlington” configuration. Patent # 2,663,806 dated December 22, 1953 by Sidney Darlington. This is a very famous patent. The Darlington configuration has been widely taught and is included in all electronics books.

In said patent, there are three drawings that are not covered by the claims of said patent. These are Figures 6, 6A and 7. All the claims involve the language “connecting two like electrodes” whereas 6, 6A and 7 do not include such structure.

Figure 6 in the Darlington patent is reproduced in Figure 1 of this patent for reference.

There is a discussion of figures 6, 6A and 7 in the body of that patent in column 6 lines 10 – 61. The discussion talks of the constants for the “equivalent single transistor” being similar to those of a single transistor and of the collector being fed by a high impedance and thus having low drift. The circuit as drawn and explained could only work in VERY special cases where currents were VERY small. There is a problem with the connection of b2 and c1 in Figure 1 (Figure 6 in earlier patent). We will use the general convention that current flow is from a more positive point to a less positive (more negative) point. This is discussed on page 2 in the reference book *The Art of Electronics* by Horowitz and Hill published by Cambridge University Press. We also have Kirchhoff’s Rule from page 3 of said reference “The sum of the currents into a point in a circuit equals the sum of the currents out”. Also from The Art of Electronics page 63, we see that, with an NPN transistor, current flows into the base and out the emitter and into the collector and out the emitter, i.e. Both I_c and I_b flow to the emitter. I_e is the sum of I_c and I_b . This is the active region of a transistor. Figure 6 (and 6A) of the Darlington patent as taught in that patent breaks Kirchhoff’s Rule; as both the collector of the first transistor and the base of the second transistor expect to sink current. There is nothing connected to this point that can source the offsetting current needed to satisfy Kirchhoff’s Rule. The patent explains some state that the circuit is in that is not the active region. In this state, the said patent gives us Figure 6A as a composite. Again, the flow of current would be into b and out of e, a condition whereby the flow of current internal to the device would flow into e_1 and out of b_1 and into e_1 and out of c_1 . A condition where only VERY small amounts of current could ever actually flow and a condition that is not all that useful.

The Darlington patent teaches that usage for Figure 6, 6A and 7, of that patent, is to create a composite transistor with better properties. The Darlington patent teaches a composite transistor where current would normally flow into the “b” terminal of figures 6, 6A and 7 of that patent. This would imply that current would then flow into the emitter of an NPN transistor and out of the base terminal. This is contrary to the normally functioning of an NPN transistor. In fact, I have never seen in the prior art any usage for the circuit in figure 6, 6A and 7 as taught in the Darlington patent. That is over a period of 50 years. This in contrast with the overwhelming use of the rest of the Darlington patent.

Beyond the basic lack of the circuit in Figure 6 of the Darlington patent to work in some useful manner, the patent does not teach any of the invention taught in this current patent. In particular, there is no teaching in the Darlington patent of how to use the element to build an amplifier, a buffer, a digital circuit or use as a cascode unit and there is no teaching in this current patent of the creation of a composite transistor. The structure may look similar in the drawing but the function and results are entirely different.

This patent is an improvement, in that it does teach how to use this proposed configuration in a useful & workable manner. Per the rules, a patent must show/teach another how to build something useful. Furthermore, the claims of this patent are an improvement and refinement to any possible reference to the topologies included in this patent in the Darlington patent. The teachings of this patent are not taught in the Darlington patent, nor do they follow from anything taught in the Darlington patent.

Current Sources

The second area is “current sources” or “constant current sources”. See Figures 2 a-f. Most of these circuits have been known and used for at least 35 years. These start simply in 2a and become more complex. The basic problem handled in 2 a-d is the base current to the two transistors with their emitters and bases connected together. The use of the extra transistor Q_{21} in Figure 2c is a better solution for an integrated circuit because a transistor takes much less space on the die than does a resistor. But the replacement of the resistor with a transistor doesn’t perform any better, it just takes less die space. In fact, it loads the current source for the “reference” transistor Q_{22} . But the circuit doesn’t have anywhere else to connect the base. The output current is less than that supplied by the resistor R_{21} . This difference in current is solved in Figure 2d by placing the transistor in a different manner. Q_{23} and Q_{24} draw $I_{22} - I_b$ and therefore Q_{25} draws $I_{22} - I_b - I_b + 2I_b = I_{22}$, where I_{22} is the current supplied by R_{22} . This is the sole reason for the use of Q_{25} in Figure 2d. In Figure 2e, we see that the only property of Q_{26} that is important is that it senses 600 mV. It acts as a switch to limit the current Q_{27} pushes through the sensing resistor R_{23} . The constant current source circuit in Figure 2e has not been used greatly as it doesn’t work well in integrated circuits as it wastes power and involves the use of a resistor that dissipates heat and uses a lot of space on a wafer. Figure 2f uses multiple (4) transistors all with the same quiescence current and much adding and subtracting of V_{be} ’s to get a stable V_{be} and therefore a stable current. There is nothing special here in any of these circuits and certainly nothing that takes advantage of the special relationship that can occur when two transistors are connected as taught by this patent. This patent teaches an improvement in that it teaches the configuration of Figures 7 (and 8 a-d) as a unique combination of transistors that is more useful than just creating constant current sources. This patent teaches the use of the proposed invention to create amplifiers, buffers, cascode other circuits, regulate voltages, create digital circuits, etc. In particular, if one examines the vast scope of the circuits that come from this invention, one can see the improvement that this patent teaches. These new circuits are not obvious as we can see by looking at the fact that the circuits in Figures 2c and 2e have been around at least 35 years and the teaching of this patent have never appeared. See figures 11 - 29.

Current Mirrors

Figures 3 a-d show examples of current mirrors. Figure 3a is the classic bipolar-transistor matched-pair current mirror. Figure 3d is the Wilson current mirror. Figure 3b is an early circuit as used in integrated circuits. Figure 3c is a modification of 3b to replace the resistor R_{31} with a transistor Q_{31} which takes less space in the die of an integrated circuit. The Wilson current mirror is an improvement on circuits 3a and 3c in that the output current is equal to the input current. This is because $I_{out} = I_{in} - I_b - I_b + 2I_b = I_{in}$ as noted above in section on current sources. Figure 3b also has the property that the output current equals the input current but uses a resistor. The use of the bipolar transistor Q_{31} in Figure 3c is used solely to get rid of the resistor R_{31} of Figure 3b as the functioning of the circuit isn't quite as good as that of 3b. The usage of Figure 3b was somewhat standard in integrated circuits at one time it appears but has been supplanted with the Wilson current mirror and its improvements. While there might appear to be some structure similarity between Figure 3c and the current proposed patent, in that the base of transistor Q_{31} is attached to the collector of the transistor receiving the reference current Q_{32} , it is by accident and not by the nature of the relationship of the two transistors. There is nothing in the usage that would lead one to see and use the relationship in some further useful manner.

Current Limit Circuits

Current limit circuits are shown Figures 4a, 4b and 5 a-d. Figures 4a and 4b are stylized circuits in that they aren't really seen in this form but add a diode in the collectors to make sure they conduce at the proper times. In practice, the circuits become different. While Figure 4a and 4b are simple examples, we generally see usage from Figures 5 a-d. Only in Figures 4a and 4b, do we see any possible structure similarity to this proposed patent. With the introduction of a diode in the collectors, that possible similarity disappears. The current limit transistors Q_{41} and Q_{42} are meant to operate only in extreme situations and not continuously. They act as a switch. Figures 5b -d are from Fairchild's *Voltage Regulator Handbook* by Andy Adamain from 1978. Figure 5a is representative of many IC current limit circuits. In Figures 5 a-d, we see the same use of the current limit transistors Q_{51} , Q_{52} , Q_{53} , and Q_{54} , BUT none of the possible similarity of Figure 4. This would lead us to believe that the secret to using the transistor in these circuits is that it can sense 600 mVolts easily. There is nothing in these usages that depends on the unique relationship or synergy that can exist between two transistors as shown in this patent. We see that the collector of the sensing transistor in these earlier circuits can be returned to many different places to effect its results. These earlier circuits work independently of whether the collector of the sensing transistor is returned to the base of the common emitter transistor whose current is being sensed. Further, in the usage as expressed in Figure 4a and 4b, when the collector of the sensing transistors Q_{41} and Q_{42} is returned to the base of the common-emitter transistors Q_{43} and Q_{44} , the signal input to the common-emitter transistor (at what we call terminal 1 in Figure 7) is a voltage driving a common emitter circuit. In contrast, in this patent application terminal 1 is fed by a current, generally a constant current. See claims 1, 2 and 3. So we see any possible structure similarity in the earlier circuits is by chance or accident and not by design and that the function and results are different than taught by this current proposed patent.

Other Prior Art

Because all the dependent claims depend on Claims 1, 2 or 3, they would by necessity be new and unique. Case in point, while there have been other amplifiers that have buffered the voltages to output transistors, the method of doing so in this patent is new, unique and an improvement. See Figure 24. Due to the wide range of applications that can be created with the use of this patent, the scope would be very great. Because the factors of new and unique are determined by the validity of the independent claims, this application does not go into all the prior art that might exist in the areas of amplifiers, buffers, etc. None are known by the applicant which would interfere. Embodiments of the independent and dependent claims are shown and explained to show how they work and how they simplify the design of other circuits.

SUMMARY OF THE INVENTION

This invention teaches an electronic building block that can be used to create other unique electronic circuits. This building block makes it easier to build complex analog circuits that are simpler with improved performance. The device uses two transistors connected with the collector of a first transistor (Q_1) connected to the base/gate of a second transistor (Q_2) and the base of the first transistor connected to the emitter/source of the second transistor. The strength of the invention is that it opens the door to more complex circuits that have not been envisioned before. It breathes new life into the bipolar transistor by taking advantage of its strengths instead of compensating for its weaknesses. The building block and the more complex circuits that come spring from it, take advantage of the inherent nature of the bipolar transistor. The bipolar transistor is by nature a current amplifying device and not a voltage amplifying device. The device shows off a synergy that comes from the particular connection of two transistors. The device's performance changes depending on the impedances of the driving signals. The control passes from one terminal to another in a smooth manner that allows a great scope of usage therefore. The device also leads to much improved use of MOSFET transistors in amplifiers and buffers.

SYMBOLS and EQUATIONS

The capital letter Q with a subscript represents transistors. Subscripts in the range 1 - 8, as shown in Figure 8 a-d, are reserved to indicate when the basic device is embedded in another application. If two devices of the same configuration are included in a circuit, an A or B is attached to the subscript. See Figure 23 as an example. If multiple usage of the device is included in an application but in Figures 8 a-d have different subscripts, then those subscripts will be used in the drawing. See Figure 24. All other transistors have numbers greater than 100. Transistors with the same subscript perform a similar function in the different drawings. The circuits build on the simple ones.

A capital letter I with a subscript indicates a constant current source in the drawings. If the subscripts are the same, then the value of currents are the same. This value of current can be altered to change the performance of the circuit. It can be optimized for the desired usage of the circuit and the properties desired. Discussion of this is included in the DISCLOSURE OF INVENTION.

The Numbers 1-4 labeling a terminal or connection in a circuit simply represents the terminal numbers as detailed in claims 1 to 3. The capital letters A, B, C, D, E, F, G, H, and V are used to indicate connection to the world outside of the circuits. The letters A and B represent the inputs. C and D are outputs and are labeled such that a negative current/voltage "into" A or B will create a positive current/voltage from C or D respectfully and visa versa. E and F are internal summing points that may be exposed to the output world to allow for customizing the circuit parameters. G and H are input and output for the digital circuits. V with a subscript and a polarity indicate a connection to a supply voltage of some useful value. V_{in} and V_{out} indicate an input signal voltage and an output voltage.

Use of capital letters R and Z are used to represent an impedance, either simple or complex. The use of R is a special case of Z as it represents a simple resistance. Generally the two are used interchangeably in this patent. Generally, any time a resistor is shown, it could be a complex impedance rather than a simple resistance. For clarity, this document will try to state when it is important or when observations can be made about the nature of that impedance as it relates to the functioning of the amplifier.

In the same manner, the use of the word "source" is intended to include "sink" depending on the polarity of the transistors involved. Also, the words "accepts" and "produces" do not imply a direction of flow (current) or a polarity of voltage.

β always indicates the beta of a bipolar transistor and does not relate to feedback factors. It is generally in the range of 20 to 200. I generally estimate it at 100 for convenience.

Any equations included in this document are derived intuitively and are to show general properties of the circuit. They are first order approximations and are not meant to be necessarily a complete representation of the circuit. They are nevertheless offered as useful in understanding the workings of the circuit. As this is a brand new area of research, much work is yet to be done on an "academic" level fully detailing the properties of the circuits. This I leave to others as the included equations are sufficient for me and others to build workable/useful electronic devices.

DESCRIPTION OF DRAWINGS

Figure 1 shows prior art. It is a copy of Figure 6 of the Darlington patent # 2,663,806.

Figure 2 (a-f) shows prior art for current sources. These are discussed in detail in the above discussion of prior art.

Figure 3 (a-d) shows prior art for current mirror circuits. These are also discussed in detail in the above discussion of prior art.

Figure 4a and 4b show prior art circuits for current limiting.

Figure 5 shows prior art for a variety of current limit circuits. These are discussed in detail in the above discussion of prior art.

Figure 6 is a dream circuit that is non-functional. Used as a point of departure.

Figure 7 shows the most simple embodiment of the teachings of this patent. Figure 8 (a-d) shows different embodiments of Claim 1. Figure 9 and 10 are the basic device and a redrawn version that shows its function in a different way. These figures relate to Claims 1, 2 and 3.

Figure 11 shows the use of two devices cascoding an operation amplifier integrated circuit. Figure 12 is just redrawn to show the nature of the cascoding more clearly. Note that the drawing uses a basic embodiment in both polarities. These figures relate to Claims 4 and 5.

Figure 13 shows the use of the two devices to create an amplifier. This figure relates to Claims 6, 7, 8, and 10.

Figure 14 shows a further modification of Figure 13 with more versatility. This figure relates to Claims 6, 7, 9, and 10.

Figure 15 shows an amplifier similar to that of Figure 14 but created with the use of the invention as detailed in Claim 3. This figure relates to Claims 6, 7, and 9.

Figure 16 shows an amplifier where all the transistors operate with the same quiescent current. This figure relates to Claims 6, 7, and 9.

Figure 17 shows the use of two devices of opposite polarity to create a buffer amplifier. This figure relates to Claims 11, 12 and 13.

Figure 18 is similar to Figure 17 but uses the device as detailed in Claim 3 to build a buffer. This figure relates to Claims 11, 12 and 14.

Figure 19 shows an amplifier from Figure 14 driving a buffer from Figure 17 to create a composite amplifier. . This figure relates to Claims 6, 7, 9, 11, and 17.

Figures 20-24 show the use of the device to create other topologies for buffer amplifiers. Figure 20 uses an extra transistor top and bottom to add even increased bias stability. Figures 21 and 22 show how the device aids in the control of a MOSFET transistor in the building of a buffer. Figure 23 includes a voltage amplifier included as a front-end to a buffer with MOSFETs as primary output devices. Figure 24 shows not only the use of the device to create the buffer but shows additionally the use of the device as detailed on claim 3 to create a form of a floating power supply for the output devices. These figures relate to figures 6, 7, 9, and 11.

Figure 25 shows an amplifier buffer combination with differential inputs and MOSFET output devices. These figures relate to Claims 4 and 11.

Figures 26 show a circuit using the device to create a voltage regulator. These figures relate to Claims 6 and 15.

Figure 27 shows a circuit using the device to create an OR gate. These figures relate to Claims 16 and 17.

Figure 28 and 29 show circuits using the device to create an NOR gate. The circuits are different in their approach to making sure that input transistors are fully on with no input. These figures relate to Claims 16, 18, and 19.

Figure 30 shows a simplified circuit to aid in understanding some of the earlier circuits. It shows a positive rail current mirror that uses an amplifier to control a MOSFET.

Figures 31 show a “block” diagram to use when examining the performance of the amplifiers, to show external hookups to an amplifier and to show the names of the external components.

DISCLOSURE OF INVENTION

While examining the subject of amplifying circuits and the weaknesses of different architectures, two advancements were made. This patent is the subject of one of those.

Using as a datum that bipolar transistors work best in a current mode, a new approach to amplifying was worked out.

Attention kept going to the circuit of Figure 6. A way just had to be figured out how to get it to work. Finally the solution as detailed in this patent became apparent.

It was clear that one had to work with current and handle items such as Miller Effect, hard saturation, Early effect, biasing instabilities, problems with level shifters, phase inverters, and buffers, etc.

After many years of research and many 100s of schematics, some common elements/solutions started to keep coming up. One common set of elements became clear and is the basis of this patent. One of these elements is represented in Figure 7. It is composed of Q₁ and Q₃ when it is made up of two NPN transistors. It is redrawn in Figures 8a-d to show both polarities and with both a bipolar transistor and a FET (MOSFET) transistor for the second transistor. Here we give labels that will be useful in later drawings to show when a version of the device is being used. In Figure 8b, the transistors are labeled Q₂ and Q₄. In Figure 8c, the transistors are labeled Q₅ and Q₇. In Figure 8d, the transistors are labeled Q₆ and Q₈. It is also redrawn in Figures 9 and 10 to show a different look at the same thing. The circuit was the results of research into the design of amplifiers, buffers, cascoding circuits and voltage regulators. As it was the results of research into so many areas, it doesn't clearly come from one area more the others. Once the device started to become clear, it was checked out in the other areas and back and forth. What became clear is that there is a synergy of two transistors when connected as suggested by this patent. The device showed special properties of great advantage over the prior art.

The uses hereby detailed are not necessarily in the order they were discovered or even most logical but in an order that goes from simple to more complex embodiments.

The basic embodiment shown in Figure 7 is much more complex in action than it appears. There is a synergy involved in that the combination is far more than the sum of the parts. In practice, terminal 1 is supplied with a current, generally a constant current. Terminal 3 is an “output”. Terminal 3 output is affected by the device but the

device is not affected by what occurs external to terminal 3 within reason. It is a high impedance. It draws a current that is determined by the device in response to what appears at all the other terminals. Terminals 2 and 4 are more complex. As an example, if the impedance at terminal 4 is much less than that at terminal 2, the voltage at terminal 4 will affect the voltage at terminal 2. As examples, see Figures 17, 18, or 21 when driving a heavy load. Because the current being driven into terminal 2 can't be "stopped" as it is a high impedance, it does affect the output current but not directly the voltage. Reversely, if terminal 2 is driven by a voltage (a low impedance) then it dictates the voltage at terminal 4. The current out of terminal 4 will be determined by the impedance (load) at terminal 4. See Figures 11, 13, 26. Most of the Figures/circuits are chameleon like in nature where the dominance changes depending of the external components. Almost any of the Figures fall into this mode. In fact when using feedback, the equations may come out easier, when examining the system in detail, from a current viewpoint rather than a voltage viewpoint. Under many conditions on a day to day basis, one can treat the amplifiers similar to common operational amplifiers. Many of the amplifiers will give better performance when treated similar to CFAs. When looking to set internal parameters or frequency compensation, it certainly is better to look to the circuit from a current aspect. Often, one can fix (lock to one value) input values to all but one terminal and let that one create all the change. Example, when used as a cascode circuit, setting the voltage at terminal 2 will set the voltage the voltage at terminal 4. Then any current variation at terminal 4 will be reflected by the same change at terminal 3. Just what one would want. Most of the circuits are more dynamic in nature and that is the real strength of the device. That synergy is what allows the device to be the core of so many circuits and do such a good job at it.

The embodiments as shown in Figures 7 and 8a-d and detailed above demonstrate examples of the means included in Claim 1. These means from Claim 1 are further illustrated in the other embodiments of the claims.

The device can be used to cascode any other device(s). This could extend from a simple transistor in an amplifier to the circuits of Figures 11 and 12. Figure 11 (and 12) shows the use of two devices to cascode an integrated circuit operational amplifier IC1. Cascoding an integrated circuit is not new. Reference my own patent # 4,797,633. But this proposed device gives much better performance in terms of lower impedance at the integrated circuit terminal 4, more accurate current drawn into the cascoding device at terminal 3 and improved frequency response as the internal "amplifying" transistor of the device is in its own right cascoded by the other transistor of the device. We see this in Figures 8 a-d. These internal transistors of the device are labeled Q_1 and Q_3 for the positive polarity device and Q_2 and Q_4 for the negative polarity device in Figure 8 a-d. In Figures 8a and 8b, the above mentioned internal "amplifying" transistors are Q_1 and Q_2 and the internal "cascoding" transistors are Q_3 and Q_4 . We see in use as a cascoding device that it is supplied a reference voltage at terminal 2. A constant current is supplied to terminal 1. Thus we get substantially a constant current through the reference unit which in this case is a zener diode D_1 . A fixed voltage is then produced at terminal 4 and the current drawn by the integrated circuit is duplicated by the current drawn into terminal 3. This is similarly done for the negative supply voltage with the use of a device as marked 1', 2', 3', 4' and zener diode D_2 . Figure 12 is just redrawn to give a different look to the circuit. The zeners can be replaced with any suitable voltage reference.

Through arrived at differently, one could look to Figure 13 as being derived from Figure 6 and the idea of being able to cascode the emitter to base and emitter to collector junctions. The input transistors are a current gain stage

cascode at about 600 mVolts. The quiescent current of transistors Q_{131} , Q_1 & Q_3 and Q_{132} , Q_2 & Q_4 are all substantially equal to the current produced by the current sources I_{13} . The current in the output transistors Q_{133} (and Q_{134}) is then $\beta_{133} I_{13}$ (and $\beta_{134} I_{13}$). The input current is the difference of that required by the two input transistors to produce a zero output current. This is $((\beta_{132} \beta_{134} - \beta_{131} \beta_{133}) / \beta_{131} \beta_{132} \beta_{133} \beta_{134}) * \beta_{133} * I_{13}$. For a match of even 100%, i.e. 2 to 1 for $\beta_{132} \beta_{134}$ to $\beta_{131} \beta_{133}$ and β_{134} to β_{133} , we get a figure of $I_{13} / (2 * \beta_{131})$. By adjusting I_{13} and matching product of the betas of the transistors, we can reduce the input current to an arbitrarily small value. When the amplifier is driven by a current, we can determine the current gain of the amplifier. $I_{out} = -I_{in} * \beta_{131} * \beta_{133}$. In practice, we can restate it in terms of voltage by looking to Figure 31 with input B grounded, $V_{out} = -I_{out} * R_L = -I_{in} * \beta_{131} * \beta_{133} * R_L = -V_{in} / R_{in} * \beta_{131} * \beta_{133} * R_L$. This gives us $A_{vol} = V_{out} / V_{in} = -\beta_{131} * \beta_{133} * R_L / R_{in}$. We can determine the loop gain by dividing by the closed loop gain i.e. $-R_f / R_{in}$. Thus loop gain is $= \beta_{131} * \beta_{133} * R_L / R_f$. The transresistance is $\beta_{131} * \beta_{133} * R_L$ or $(\beta^2 R_L)$. This is similar that of a CFA or Current Feedback Amplifier. Transresistance for a typical CFA is 100K. Our value above is normally much greater. One of the best discussions of current feedback amplifiers (CFA) is Burr Brown Application Bulletin #193 *THE CURRENT-FEEDBACK OP AMP A HIGH SPEED BUILDING BLOCK* by Anthony D. Wang and *Analog Circuit Design* (Edited by Jim Williams) Chapter 25 *Current-Feedback Amplifiers* by Sergio Franco. Trying to compute a voltage gain of the amplifier is much more complex. It is not very informative and for most applications we can use the above formula. When operated as an inverting amplifier with a fixed voltage (generally ground), the amplifier follows the rules for a current feedback amplifier. Even when operated as a non-inverting amplifier, the amplifier operates as a CFA as regards to negative feedback. It accepts then a voltage input at the non-inverting input, but still has all the benefits of a CFA.

The input transistors Q_{131} and Q_{132} have a constant voltage across them of about 600 mV and draw current in the order of μ Amps. The heat dissipated is therefore on the order of μ Watts. The input transistors are the most important in determining the performance of the circuit. They can be chosen for high current gain, high frequency response, matching with the other input transistor, etc. When R_f is chosen to be approximately equal to $\beta_{133} * R_L$, then loop gain is approximately equal to β_{131} . The loop gain doesn't go to 1 until the F_T of the transistor. This is of the order of 100 to 1500 MHz. As the loop gain is only dependant on R_f and not R_{in} , the amplifier could have a gain of 100 and still have a -3db point of several hundred Mhz. Offset and input impedance are discussed in detail with later circuits. Most of the discussion is similar from one amplifier to another. Please note that the circuit in Figure 13 has a -40db roll off and therefore generally needs some kind of frequency compensation. In this circuit, the possible choices are a capacitor on the load or using slower transistors for the input transistors. Circuits to follow have more options for compensation. Even a capacitor on R_f could stabilize the circuit. It does so by extending the loop gain and roll off rate. It is very practical and useful.

Figure 14 is a modification of 13 to unlock the input(s) from ground and increase common mode range. By connecting the collectors of the input transistors Q_{141} and Q_{142} to suitable fixed supply voltages, we get an improved common mode voltage range for the input. We also see we can then unlock the connection of the emitters of transistors Q_1 & Q_2 from ground and use that point as another input; a non-inverting input. We now have a differential amplifier. We can use the equations for gain and loop gain in the discussion of Figure 13. See Figure 31 for connection of external components. Of course, there is only one feedback resistor, as there is only one output

and therefore only one inverting input to be connected. By setting gain resistors for the inverting side, we get a circuit where the amplifier acts as a non-inverting amplifier with a fixed gain when driven by a voltage at the non-inverting input. When driven by a current, the response becomes much more complex and unpredictable. One could also, connect the inverting input to the output and we would have a buffer amplifier, i.e. an amplifier with a gain of +1. A variation of this is shown in Figure 20.

Figure 15 is a modification of Figure 14 showing the use of a MOSFET transistors Q₇ and Q₈ as detailed in Claim 3. Transistors Q₁₅₁ and Q₁₅₂ are used for the input gain stage and Q₁₅₃ and Q₁₅₄ are used for the output gain stage. The quiescence current of all the transistors is the same as in Figures 13 and 14. All the equations for gain are still the same. The advantage of this circuit is the increase of maximum current available to quiescence current. In Figures 13 (and 14) that ratio is limited to β_3 (or β_4) as the output current is limited to $I_{13} * \beta_3 * \beta_{133}$. The available output current for Figure 15 is limited only by the limits of the transistors and available input current as the output current is still $I_{out} = I_{in} * \beta_{151} * \beta_{153}$. With 1 mA current input, the circuit can still produce many Amperes of output current. This is very good for a circuit with little or no cross-over distortion. The reasons for the low distortion is that the transistors are driven with current and not voltage, only turn off under extreme conditions and don't rely on emitter follower circuits.

Figure 16 is a modification of Figure 14 showing an amplifier where all the transistors have the same quiescence current. To the output gain stage transistors Q₁₆₄ and Q₁₆₃ have been added two diode-connected transistors Q₁₆₁ and Q₁₆₂. As the output quiescence current is reduced by a factor of β the circuit is generally operated at a higher quiescence current for the input transistors and as a result the frequency response is improved. The gain is reduced by a factor of β . Under most conditions this leads to a more stable amplifier as the gain response rolls off at only 20 db per decade, rather than 40 db in the earlier amplifiers (Figures 13-15). Thus this configuration might be best for high frequency operation. This is at the benefit of reduced output current availability. The circuit would also have a lower input impedance but that is generally not a problem with higher speed amplifiers as they are operated with lower impedances. The concern could be the same as with any CFA where there is a problem with non-zero input impedances.

Figure 17 is a buffer. It uses two proposed devices along with two additional transistors Q₁₇₁ and Q₁₇₂ and current sources I₁₇ to create a buffer able to handle both positive/negative voltages/currents. It is a voltage buffer but can appear to be a current buffer. However it appears, it really is only a voltage buffer with high current gain. It appears when driven by a current, that the output is a function of input current. What really occurs is that the output current develops a voltage across a load and that voltage is reflected back to the input, where the input signal was a current (high impedance). We could better view it as an input current driving a high impedance (the input of the buffer) which will give a voltage. This shows the chameleon like nature of the proposed invention. Otherwise, looking at the circuit, we see that the output is equal to the input voltage plus 600 mV minus 600 mV or on the flip side the output is equal to the input minus 600 mV plus 600 mV. In either case, the output is equal to the input. The only error being offset voltages due to differences in base-emitter voltages when some transistors draw more current than others, mostly of a dynamic nature. This is usually the case with buffers and the reason they are generally used inside a feedback loop with the driving force coming from an operational amplifier. The operational amplifier with

feedback will keep any offset near zero. In detail, we see in the circuit that when the input voltage rises, less current is drawn by transistor Q_1 and therefore more current from the current source I_{17} will drive transistor Q_3 and thus Q_{171} , leading to more output current and a rise of the voltage across a load until the voltage across the load is substantially the same as the input. For a negative signal, the action is performed by Q_2 , Q_4 , and Q_{172} . While the above is taking place, that is a signal goes high, the input is also driving current into Q_3 and thus turning the negative side off at the same time the positive side is being turned on and visa versa. Only under extreme cases does one side or the other ever turn completely off. The reason is that the voltage across the bases of Q_{171} and Q_{172} is always equal to approximately 1.2 volts, the voltage generated by the two input base emitter voltages. If one of the output transistors develops a voltage great enough, it can steal off this "bias" voltage and turn off the other output transistor. Note that there is a fault condition that can occur with this circuit. If the output load is "locked" in some manner to a voltage (like zero) and the input voltage goes high (or low) greater than the zener voltage of one the input transistors, the input transistor will fail. The solution is shown included in the schematics of Figures 20, 21, and 24. It consists simply of two zeners back to back from the input to the output. The zener diodes must be able to withstand any current that is supplied by the input source. They are not shown in Figure 17 for simplicity sake and to show the circuit in its simplest form. The voltage gain of the circuit is close to +1. The current gain is simply: $\beta_3 * \beta_{171}$. The input impedance is $\beta_3 * \beta_{171} * R_L$ or $\beta_4 * \beta_{172} * R_L$ depending on the polarity of the signal. The ratio of maximum output current to quiescent current is $\beta_3 * \beta_{171}$ (or $\beta_4 * \beta_{172}$). This is a very good ratio, indeed. Most buffers have a figure of the order of β , not β^2 , as we have here.

Figure 18, is just a modification of Figure 17 to allow the use of FET (MOSFET) transistors Q_7 and Q_8 as detailed in claim 3. This circuit has even higher current gain though it isn't as easy to just write an equation. But a VERY high input impedance. The circuit does either require separate higher voltage supplies to drive the current sources or the output is limited in voltage due to the need for a higher driving voltage to the MOSFETs. The ratio of available output current to quiescent current is much greater than that of Figure 17.

Figure 19 shows a combination of an amplifier (Figure 14) and a buffer (Figure 17) to form a composite amplifier. This amplifier would be suitable for inclusion in an integrated circuit as an operational amplifier. It lends itself well to such an application as there are no resistors in the circuit. The current sources could possibly require resistors but a minimum number as these current sources could be connected and reflected from and thus all stem from actually one constant current source. The amplifier would need to be frequency compensated with the use of a resistor and/or capacitor at the internal connection of the amplifier and buffer, labeled as Point F. Where Z_f is the impedance of the external components at point F and is less than the input impedance of the buffer at point F, we see the transresistance of the circuit is $\beta^2 * Z_f$. This formula shows that there are many options in configuring the performance of the amplifier. Alternatively, one could use an amplifier with current mirrors such as Figure 16 for the amplifier portion.

Figure 20 shows another buffer. Transistors Q_{201} and Q_{202} are used for the input gain stage and Q_{203} and Q_{204} are used for the output gain stage. It is a modification of the amplifier of Figure 14 to create a +1 gain amplifier. It has added stability due to the addition of a degeneration resistors R_{201} and R_{202} . Most of the parameters of the circuit are similar to those of the other buffers detailed above. The gain is +1. Many of the properties of the circuit could

be altered by changing the value of these resistors R_{201} and R_{202} . These parameters would include the quiescent current of the output transistors Q_{203} and Q_{204} , and the input impedance of the amplifier. This is a very stable configuration. One could remove the resistors by placing the input transistors Q_1 and Q_2 thermally near the output transistors.

Figure 21 shows a more complex buffer. It shows how to use MOSFETs to boost the available output current. It is a modification of Figure 17 with the output transistors now labeled as Q_{219} and Q_{220} and means to take the current from the collectors of Q_3 and Q_4 to drive a boosting circuit which includes MOSFETs Q_{213} and Q_{214} . The drive circuitry to the MOSFETs Q_{213} and Q_{214} for the upper and lower halves of the circuit is composed of transistors Q_{211} , Q_{213} & Q_{215} and Q_{212} , Q_{214} and Q_{216} . Resistors R_{213} and R_{214} are used to convert the current to a voltage to drive the MOSFETs. Resistors R_{211} and R_{212} are used to increase the quiescent current of Q_3 and Q_4 . The circuit functions by sensing the current drawn by Q_3 in response to a negative input signal and mirroring it to drive a ground connected transistor of Q_{215} that drives the gate of a MOSFET transistor Q_{217} thus supplying current in increasing amounts to the output. Resistors R_{213} and R_{214} are selected so that any voltage developed across them under quiescent conditions will not turn on the MOSFETs. The quiescent current driving R_{213} is $\beta_7 \cdot (600\text{mV} / R_{211} + 2 \cdot I_{21})$. If R_{213} is made small, the high frequency performance increases because of the gate drive capability. The only price paid is increased thermal dissipation for Q_{215} and Q_{216} . One could use current sources for R_{213} and R_{214} . Before the MOSFETs start to conduct, the circuit performs exactly like Figure 17. Note also the addition of the back to back zener diodes D_3 and D_4 to protect Q_1 and Q_3 . Anti-saturation diodes D_1 and D_2 prevent the output transistors (Q_{217} , Q_{218} , Q_{219} and Q_{220}) from going into saturation. Whenever the voltage across any of them becomes less than approximately 600 mV, the diodes will conduct and limit the drive current available thus preventing them from being driven any closer to saturation. It is ideal that the supply voltage at the bases of Q_{211} and Q_{213} is higher than that supplying the output transistors so the output can be driven to within 600mV of the output supply voltage. All this discussion applies to the lower half of the amplifier for the conduction of input signals of a positive polarity that drive the output toward the negative supply. Only different part numbers are applicable.

Figure 22 shows the use of the proposed device to create another buffer. In this circuit, the device is used as a floating amplifier to control the output current of the buffer. There are two embedded amplifiers, one for the positive current and one for the negative current. The quiescent output current is sensed by two output resistors R_{221} and R_{222} . The amplifier adjusts the drive on the MOSFETs to match the output current to that requested by the input, which in this case is sensed across another set of resistors R_{223} and R_{224} . The two embedded amplifiers are composed of transistors Q_2 , Q_4 , Q_{221} , Q_{223} , and Q_{225} for the positive side and transistors Q_1 , Q_3 , Q_{222} , Q_{224} , and Q_{226} for the negative side. The input resistors R_{223} and R_{224} are driven by a constant current supplied by Q_{227A} , Q_{227B} , Q_{228A} , Q_{228B} , and constant current source I_{22} . Each embedded amplifier is similar to half of Figure 14. Transistors Q_2 and Q_4 "cascode" a voltage at the emitter of Q_{221} equal to that at the emitter of Q_2 plus approximately 600mV. A higher voltage at the base of transistor Q_{221} than the emitter of Q_2 will cause Q_4 to drive Q_{223} which in turn drives transistors Q_{225} and raise the output current and voltage until the voltage at the emitter of Q_2 matches that at the base of transistors Q_{221} . With increased current output, the voltage across resistor R_{221} will be more than that across R_{223} . Therefore the drive voltage to the input of the buffer will have to be higher than the

output. This means the voltage gain of the buffer is less than one. This condition is usually handled by including the buffer inside a feedback loop with an operational amplifier. The same fault condition could apply here as in earlier buffers when the input becomes greater than the output by more than the zener breakdown voltage of Q_2 and the same solution handles it, i.e. back to back zener diodes from input to output. The current could be limited by resistors R_{223} and R_{224} and the impedance of the source but it is the voltage that kills the transistor and not current in this mode. These zener diodes are not shown in Figure 22. The amount of drive current needed from the constant current sources is very small as that current is multiplied by Q_{221} and Q_{223} to drive Q_{225} . All this discussion applies equally to the negative side of the buffer, only with different components and polarities.

Figure 23 shows another amplifier and buffer circuit that is built around the use of the proposed device. In fact there are 4 devices used in Figure 23. They are noted as A and B added to the subscripts for the transistors, i.e. Q_{1A} , Q_{1B} , Q_{2A} , Q_{2B} , Q_{3A} , Q_{3B} , Q_{4A} , and Q_{4B} , to make it easier to spot where the devices are located. This circuit uses 2 of the devices to create the amplifier front end. Transistors Q_{231} and Q_{232} are used for the input gain stages and Q_{233} and Q_{234} are used for the output gain stages of the amplifier portions of the circuit. Quiescent currents are set by current sources I_{23} . In this case, the output current of the amplifier portion is very tightly controlled. Transistors Q_{235} and Q_{236} are used for the input gain stages and Q_{239} and Q_{240} are used for the output or driver gain stages of the output portions of the amplifier. These output amplifiers drive transistors Q_{237} and Q_{238} to complete their portions of the circuit. The output amplifier portions will operate to keep the voltage dropped across R_{231} and R_{232} duplicated exactly across R_{233} and R_{234} . The output current is a multiple of the current through R_{231} and R_{232} . Therefore the ratio of available output current to quiescent current is the same as that of the amplifier portion. This ratio is generally limited to the order of β . If the output resistors R_{233} and R_{234} are .1 Ohms and the “driving” resistors are 100 Ohms and are driven with 50 μA then there is 5 mV across both sets. The quiescent output stage current is then 50 mA. A drive of 10 mA through R_{233} would produce 10 Amps output current. The amplifier buffer combination has a roll over of 40 db per octave and so will need some compensation to be stable. There are several places a capacitor could be placed including a) output to ground b) from base to collector of transistors Q_{233} and Q_{234} c) across R_{231} and R_{232} d) across the feedback resistor. Another approach would be to enhance the high frequency response of the amplifier to keep the loop gain from reaching zero “too” early. This could be accomplished with capacitors across resistors R_{233} and R_{234} . With the high output power capability from the use of MOSFETs Q_{237} and Q_{238} , the exact control of these MOSFETs, and the high performance amplifier front end, this is a very high quality circuit. It is stable, easy to design for, requires no matched parts to function and can be customized to meet almost any need. A quick look at offset is useful here. The input offset of the amplifier is that current needed to produce a zero output current or voltage. In this case, that would substantially met when the voltage across R_{231} and R_{232} are equal. The upper current and lower current of the amplifier portion of the circuit are equal. Thus the input (offset) current would be $= (1/(\beta_{231} * \beta_{233}) - 1/(\beta_{232} * \beta_{234})) \beta_{234} * I_{23}$ where β_{234} is assumed larger than β_{233} . Worst case assume that $\beta_{232} * \beta_{234}$ is much larger than $\beta_{231} * \beta_{233}$ then input current will be $(\beta_{234} / (\beta_{231} * \beta_{233})) * I_{23}$. If $\beta_{234} = 2 * \beta_{233}$ then Input current will be $2 * I_{23} / \beta_{231}$. A possible value of I_{23} is 1 μA . A value of $\beta_{231} = 50$ would give an input current of 40 nAmps. If all the input current were supplied by an input resistor R_{in} (as shown in Figure 31) of 500 Ohms, then the output offset would be 2 μV . If all the current were supplied by a feedback resistor R_f (as shown in Figure 31) of 5000 Ohms, then the output offset voltage would

be $20\ \mu\text{V}$, independent of the closed loop gain of the amplifier. These figures could be improved by proper design of an integrated circuit. When used for a DC Amplifier measuring small voltage across very low impedances, all the input current would come through R_{in} , which could be made even smaller than 500 Ohms. A possible value could be 10 Ohms. This would give an output offset voltage of $.4\ \mu\text{V}$. When used with an R_f of 1000 Ohms, the amplifier would have a gain of 100. The output offset reflected back to the input would appear as 4 nVolts. Layout and physical aspects of the circuit would take priority in keeping to offset low.

Figure 24 shows the use of the device to create a high performance buffer. There are 4 uses of the device in this buffer. A pair to create the buffer itself and another pair to create the floating buffered power supply for the output devices. The main part of the buffer consists of transistors $Q_1 - Q_4$, Q_{241} and Q_{242} and current sources I_{24} . The output transistors Q_{241} and Q_{242} are cascoded by the third and fourth usages of the device. Q_5 & Q_7 and Q_6 & Q_8 produce an exact low voltage across the output transistors. A voltage of 1.8 volts might be appropriate. Maybe higher might be needed to give greater range and holdup. This voltage is determined by zener diodes D_{241} and D_{242} . The voltage seen by the output transistors at their collectors then would be + and - that zener voltage plus approximately 600mV for the V_{be} voltages of transistors Q_5 and Q_6 . Capacitors C_{241} and C_{242} are hold up units. They hold and supply most of the power used by the output transistors. Even when a MOSFET might be turned off because there is no headroom for it to operate, there would still be power for the output transistors. As long as the current sources I_{241} and I_{242} have enough voltage headroom of their own to drive the output transistors, the output of the buffer could go higher than the main power supply voltage. The schematic shows bootstrapping to give enough voltage to drive the MOSFETs but that same bootstrapping could be used to supply the other current sources. Note also that the unit has anti-saturation diodes D_{243} and D_{244} . Whenever the voltage across Q_{241} or Q_{242} becomes less than about 600 mV the anti-saturation diodes start to conduct and prevent any more drive thus preventing the output transistors from going into saturation. This is very important when using high gain amplifiers as they tend to go into saturation very hard because of the intention of the amplifier to get its way and move that voltage even higher when there is no supply voltage left to do so. Transistors when driven in this manner can stay in saturation for a long time. A very serious source of distortion.

Figure 25 uses four of the proposed devices to create a very exacting amplifier. The amplifier has a front end composed of two proposed devices configured similar to Figure 14 with input gain stage transistors Q_{251} and Q_{252} without the second stage current gain transistors. Transistors Q_{1A} , Q_{2A} , Q_{3A} , and Q_{4A} are the transistors of the front end. The current input after being amplified and passing through the proposed devices drives resistors R_{251} and R_{252} . The voltage across these resistors R_{251} and R_{252} is duplicated across resistors R_{253} and R_{254} by the embedded amplifiers composed of Q_{1B} , Q_{3B} , Q_{253} , Q_{255} , and Q_{257} along with R_{253} & R_{255} and current source I_{25A} for the upper half and by Q_{2B} , Q_{4B} , Q_{254} , Q_{256} , and Q_{258} along with R_{254} & R_{256} and current source I_{25A} for the lower half. See Figure 30 for a simplified circuit that shows a positive rail voltage mirror. That is basically what is being done here. If the drive current from Q_{251} increases the current across R_{251} , Q_{1B} will draw more current from current source I_{25A} and thus turn Q_{3B} off lowering the drive to Q_{255} and thus across R_{255} and turning MOSFET transistor Q_{257} further on until the voltage across R_{253} increases to match that across R_{251} . This increased current from Q_{251} in response to a negative current/voltage will cause the output current to increase thus increasing the output voltage. A positive input will cause the lower portion of the circuit to draw current causing the output to go low. It is clear

then that A is an inverting input and suitable for negative feedback. The quiescent current of the transistors in the amplifier front-end are all the same and equal to the current from the current sources I_{25} . This current also goes through resistors R_{251} and R_{252} . As an example, assume R_{251} (& R_{252}) are equal to 100 Ohms and that I_{25} is set to 50 μ A giving a voltage of 5 mV. This same 5 mV across R_{253} (and R_{254}), which are equal to .1 Ohms, causes 50 mA quiescent current to flow in Q_{257} and Q_{258} . If we use high gain transistors for Q_{251} , Q_{252} , Q_{3A} , and Q_{4A} with a beta of 200, then at maximum drive we get 10 mA current through R_{251} (or R_{252}) and 1 Volt. The 1 Volt in turn causes 10 Amps to flow through R_{253} and Q_{257} (or R_{254} and Q_{258}) into an output load. We can figure the voltage gain of the device as follows:

$$V_{out} = I_{out} * R_L = \beta_{251} * (R_{251} / R_{253}) * I_{in} * R_L = \beta_{251} * (R_{251} / R_{253}) * R_L * V_{in} / R_{in}$$

$$A_{vol} = V_{out} / V_{in} = \beta_{251} * (R_{251} / R_{253}) * (R_L / R_{in})$$

$$\text{Loop Gain} = \beta_{251} * (R_{251} / R_{253}) * (R_L / R_{in}) * (R_{in} / R_f) = \beta_{251} * (R_{251} / R_{253}) * (R_L / R_f)$$

$$\text{Transresistance} = \beta_{251} * (R_{251} / R_{253}) * R_L$$

We see from the loop gain equation that the amplifier has only one dominant pole and therefore stable. If we selected resistors such that $(R_{251} / R_{253}) * (R_L / R_f) = 1$, then the Loop Gain would = β_{251} . We see that the zero intercept would not come until $\beta_{251} = 1$, which is F_T for that transistor. This is a very high cutoff point. This is especially high for an audio amplifier, which normally extends maybe to 1 MHz but rarely higher. In fact, an input filter is generally used to keep these kinds of frequencies from reaching the amplifier. There are several ways to compensate the amplifier for frequency stability or to reduce the frequency response. One could add capacitors across R_{251} (and R_{252}) or across the load R_L . One could use lower frequency input transistors. One could extend the zero loop gain point by adding a capacitor across R_{253} (and R_{254}) or across the feedback resistor R_f (at the expense of closed loop frequency response). A combination of capacitors could be used to tailor the response. Some things need to be noted about the circuit. A higher supply voltage is needed for I_{25A} and Q_{255} (and Q_{256}) to allow the transistors to sense a voltage that is so near the output power supply rails. The ratio of available output current to quiescent current is limited to the beta of transistors Q_{3A} and Q_{4A} . A fault mode that is possible in some of the circuits detailed in this application does not apply to this one as the current drive from the input transistors is not enough to drive R_{251} (or R_{252}) to a voltage greater than the zener voltage of the base-emitter of Q_{253} (or Q_{254}). A look at the input current (offset) of the circuit, using R_f of 100,000 and a 20% match of β_{252} and β_{251} , gives us the following:

$$I_{offset} = I_{25} / \beta_{252} - I_{25} / \beta_{251} = .2 * I_{25} / \beta_{251} = .2 * 50 \mu\text{A} / 100 = 100 \text{ nA}$$

$$V_{offset} = R_f * I_{offset} = 100,000 * 100 \text{ nA} = 10 \text{ mV} \quad \text{at the output} \quad \text{worse case}$$

For a large high current output amplifier driving 8 Ohms, this is just fine. $10 \text{ mA} * 80 \text{ mV} = 800 \mu\text{Watts}$.

Figure 26 shows the use of the device to create a voltage regulator. It is similar to the amplifiers detailed earlier. Transistors Q_1 , Q_3 , Q_{261} , and Q_{262} along with current source I_{26} and gain setting resistors R_{261} and R_{262} compose

the amplifier. The zener D_{261} supplies a reference voltage but could replace with any kind of voltage reference such as band-gap or sub 1 volt references. Examples of sub 1 volt references are detailed in *Monochip Application Note APN-25* by Interdesign – A Feranti Company titled *Low Voltage Bipolar Circuits* by Derek Brey. They show stable reference voltages below 200mV. With no load, the quiescent current of all parts of the circuit are the same and equal to I_{26} . Therefore R_{261} must be less than the zener voltage of D_{261} divided by I_{26} for stable operation. Maximum current output is $\beta_3 * \beta_{262} * I_{26}$. The quiescent current is $2 * I_{26}$. The ratio is $\beta_3 * \beta_{262} / 2$. This is a good measure of a regulator. The regulator can regulate down to the reference voltage. The circuit does require some headroom as configured. The input supply voltage must be greater than the reference voltage by 1.2 to 1.6 volts depending on output current demands. The circuit can regulate to 600 mVolts using a diode as the reference. Below this one would have to split the voltage from a diode reference or use a sub 1 volt reference to get a smaller reference voltage at the emitter of Q_1 . Diodes aren't very good references due to temperature drift and tolerances. But for many applications they can work just fine, particularly at very low voltages. The circuit can convert any input voltage greater than about 2 volts to any of .6, 1.2 or 1.8 volts very handily.

Figure 27 is the first digital circuit of this application. It is an OR circuit and uses the proposed device (transistors Q_1 and Q_3) to cascode a common emitter input transistor Q_{271} . With no input the output current from transistor Q_{272} is $\beta_{272} / \beta_1 * I_{271}$. If I_{272} is twice the current of I_{271} , then the output should be low. If any input is high, then the output current will at a maximum $= \beta_3 * \beta_{272} * I_{271}$. This ratio is $= \beta_1 * \beta_3$. A very good measure of fan out for a digital circuit. The supply voltage appears to need to be about 1.2 volts to function. The voltages are distributed a little differently whether the circuit is on or off but the voltage needed is about the same. A limit must be placed on the input current. A choice is to limit the input current to that of I_{271} , the largest usable amount of current that can increase the output current. With the small supply voltages being used, a volt drop should be plenty. $R_{input} = 1 / I_{271} = 1 / 10 \mu A = 100K$. A better solution in an integrated circuit can be devised and save the space required by such a large resistor. This circuit is all based on current steering and has the potential to be very fast. One can vary the supply voltage and currents used internal to get the kind of performance desired. The circuit is suitable to drive large amount of current into a load. If I_{271} is set to 1 mA then a drive of 1 mA into the circuit will produces many Amperes of current out. And of course it could be operated from a much higher supply so that output could be great indeed.

Figures 28 and 29 are very similar. They are both NOR gates. The difference is that Figure 28 uses dual input transistors Q_{281} and Q_{282} in parallel to reduce the base emitter voltage to less than that of Q_1 , whereas Figure 29 inserts a diode D_1 between the emitter of Q_1 and ground to make sure the voltage at the base of Q_1 is higher than the base-emitter voltage of Q_{291} . Both cases desire that Q_{291} (or Q_{281} and Q_{282}) will be fully on under no input conditions. In both circuits, a high input voltage (current) will saturation the current source I_{281} (or I_{291}) and turn Q_{291} (or Q_{281} and Q_{282}) off. When Q_{291} (or Q_{281} and Q_{282}) turns off, the circuit reverts to a low current condition. The amount of current that will then flow from the output transistor Q_{282} (or Q_{293}) is $\beta_{282} / \beta_3 * I_{282}$ (or $\beta_{293} / \beta_3 * I_{292}$). If I_{283} (or I_{293}) is twice I_{282} (or I_{292}) then the output will go low. One does not have to limit the input current, as the input will only draw I_{281} (or I_{291}). The available output current for Figure 29 is $\beta_3 * \beta_{292} * I_{292}$ or $\beta_{291} * \beta_{292} * I_{291}$, whichever is lower. The available output current for Figure 28 is $\beta_3 * \beta_{283} * I_{282}$ or $\beta_{281} * \beta_{283} * I_{281}$, whichever is lower. The ratio of available output current to quiescent current is of the order of β^2 . This is a high

fan-out for a digital circuit. It could even be used to drive fairly large loads. The circuits function on current steering and thus are very fast. The circuit in Figure 29 requires 600 mV more supply voltage than the circuit in Figure 28. Figure 28 might be able to operate from as low as 1.2 volts.

From the forgoing, it should be clear that the present invention may be embodied in forms other than those described above. The above-described examples are therefore to be considered in all respects illustrative and not restrictive or limiting, the scope of the invention being indicated by the appended claims rather than the foregoing. All changes that come within the meaning and scope of the claims are intended to be embraced therein

Advantages

The advantages that can be gained by using the proposed device fit in the following :

1) Low Voltage Operation

Many of the amplifiers/buffers can operate at voltages less than ± 1.5 volts.

2) Low Offset and Noise

See discussion under Figure 23 and 25.

3) Extended Frequency Response

As many of the amplifiers operate as CFAs, the frequency response is very good. See discussion under 13 and 25.

4) Configurable for Low Power to High Power Operation

Figure 16 could be configured with ± 1.5 volt supply and quiescent current drain of 30 μ A. Total power of 90 μ W. Very good performance. Some of the designs could be configured for very large power output. Thousand of Watts output could be produced and still have stability in the internal circuit currents. See 9 below.

5) Simplicity

Circuit designs are simpler than previous circuits. Complete operational amplifiers can be built around 8 transistors and 2 current sources (Figure 15). High current gain buffers can be built with 6 transistors and 2 current sources (Figure 17 & 18).

6) Stability – Internal Currents

Quiescent currents are exactly controlled. Even for MOSFETs.

7) No Saturation

Inherent in the use of the device is that new configurations prevent transistors from going into saturation. Figure 13 only the output transistors can go into saturation. Figure 17 only the current sources are a concern. Figures for the more complex buffer circuits lend themselves very easily to the addition of an anti-saturation diode (Figures 21 and 24).

8) Lower Distortion – No CrossOver Distortion

Because of the control of quiescent currents and the inherent way the invention works, only under extreme conditions do any transistors even get turned off. There is a passing of current going on and no dead spaces that a voltage must pass through to elicit a response. In Figures 13 and 17, even the smallest amount of input current/voltage will produce an output change.

9) High ratio of output current to quiescent current

Previous designs generally must settle for a ratio of available output current to quiescent current of β . In many of the circuits detailed in this patent, the ratio is β^2 . Those circuits that use Figures 8c and 8d, i.e. use MOSFETs, the ratio is much higher (Figures 15 and 18).